

Comparison of Poole-Frenkel and Hartke Emission Currents in a Capacitive Micromachined Ultrasonic Transducer (CMUT)

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Chukwuebuka received his Bachelor's degree in Electrical and Electronics Engineering from the Jawaharlal Nehru Technological University, Kakinada, India, in 2020, and his master's degree in Electrical and Computer Engineering, from the University of Windsor in 2025.

His research interests are focused on theoretical and experimental investigations of fundamental physical principles related to microelectromechanical systems (MEMS) devices, specifically, Capacitive micromachined ultrasonic transducers (CMUTs).

- Dielectric charging in Capacitive Micromachined Ultrasonic Transducers (CMUTs) is a major reliability challenge for their mainstream adoption despite their superior performance compared to the conventional piezoelectric ultrasonic transducers.
- This research work investigated the dielectric charging in CMUTs built with silicon nitride membranes.
- The investigation revealed that the charges emitted from the K-center traps in the silicon nitride membranes are the main source of CMUT dielectric charging.
- The investigation compared the emission current density from the trap centers due to the internal Schottky effect using the 1D Poole-Frenkel and the 3D Hartke models.
- It was observed that the Poole-Frenkel model consistently predicts higher current densities exceeding the Hartke model predictions by more than 99% for a bias voltage range of 11–77 volts.
- The study provides valuable insights into the dielectric charging mechanisms in CMUTs, which can aid to design CMUTs with improved reliability.

Introduction: Capacitive Micromachined Ultrasonic Transducer



- CMUT is a reciprocal electrostatic transducer that rely on electrostatic or acoustic vibration of a microfabricated membrane to receive or transmit ultrasound.
- Ultrasound is a mechanical wave having a frequency range higher than the audible frequency of humans and propagates through solid and fluidic mediums.
- Ultrasound at various intensities can be used for diagnostic imaging, treatment, non-destructive evaluation of materials, ranging, and many others [1]-[3].
- The CMUT faces a reliability issue due to charge accumulation in the dielectric material, which must be resolved for its mainstream adoption [4]-[6].

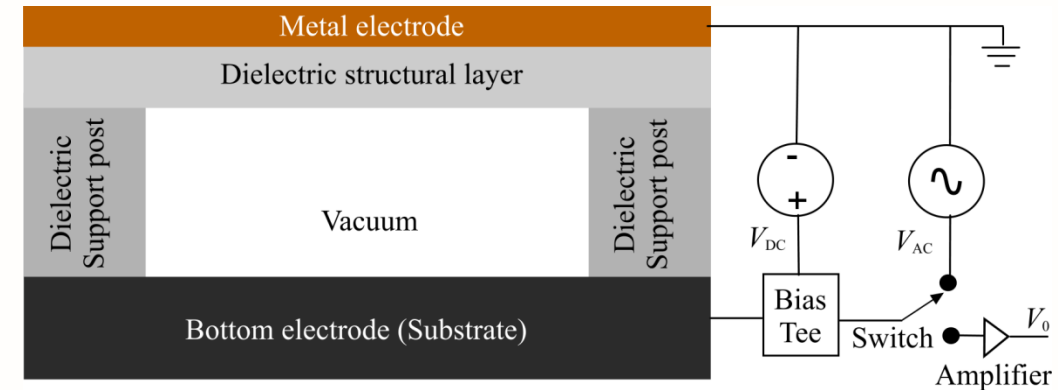


Figure 1. A typical CMUT geometry in an operational setup.

Introduction: Capacitive Micromachined Ultrasonic Transducer



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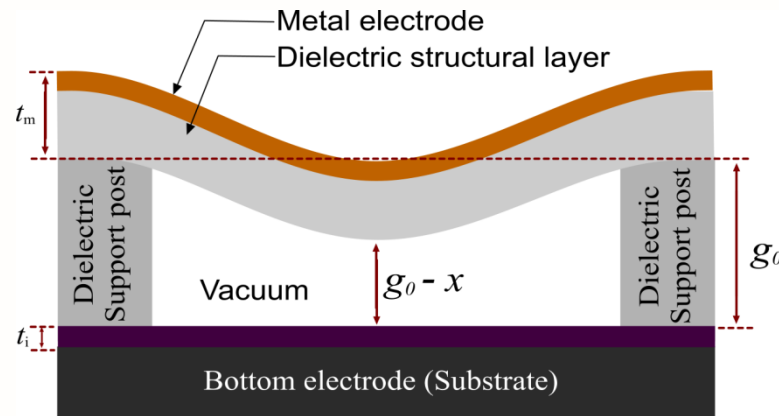


Figure 2a. Deflection in CMUT.

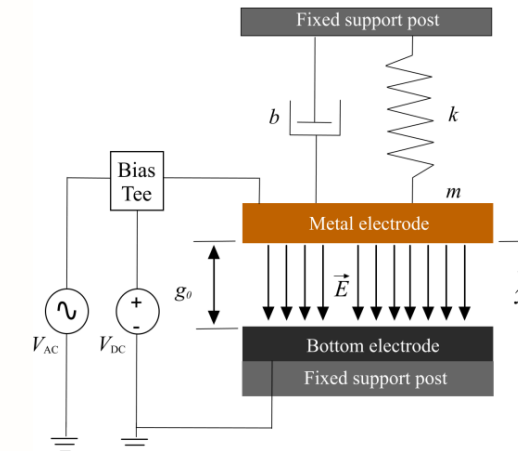


Figure 2b. Electromechanical model of a CMUT.

- A CMUT consists of a flexible top plate anchored around its edges and suspended over a gap formed between the flexible top plate and a fixed bottom plate [3].
- The device can be modelled as a variable capacitor, where the vibrational behavior of the plate can be modeled using a mass-spring-damper system.

$$m \frac{d^2 x}{dt^2} + b \frac{dx}{dt} + kx = F \quad (1)$$

$$F = \frac{\epsilon_0 \epsilon_r A V^2}{2(g_{\text{eff}} - x)^2} \quad (2)$$

$$C(x) = \frac{\epsilon_0 \epsilon_r A}{g_0 - w(x)} \quad (3)$$

$$g_{\text{eff}} = \frac{t_i}{\epsilon_r} + \frac{t_m}{\epsilon_m} + g_0 \quad (4)$$

Introduction: CMUT Operating Modes



Transmit Mode:

- When an AC voltage of desired amplitude and frequency is superimposed in addition to the bias voltage, the CMUT operates in the Transmit mode [7].

Receive Mode:

- When the biased CMUT is exposed to an incoming ultrasonic wave, the CMUT operates in the Receive mode [7].

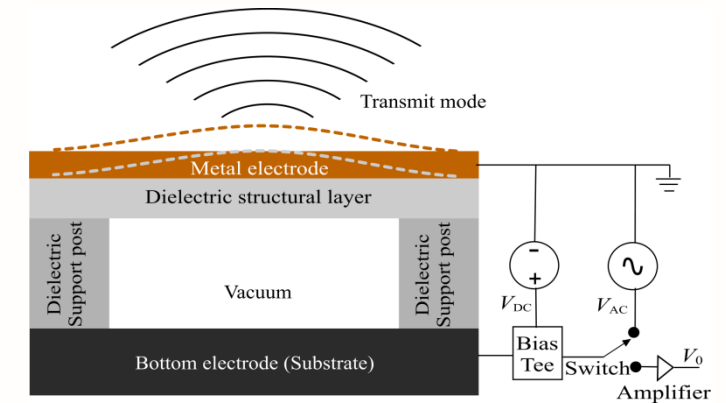


Figure 3: Transmit mode operation of a CMUT.

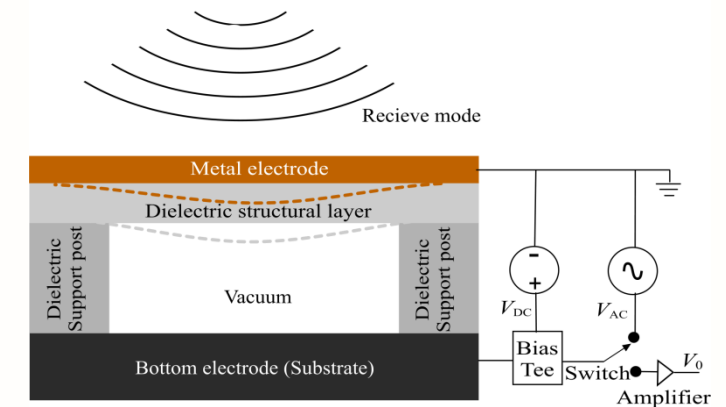


Figure 4: Receive mode operation of a CMUT.

Dielectric Charging

- Dielectric charging is a critical issue that compromises CMUT operation.
- This affects CMUTs medical, therapeutic, and industrial applications by causing **Reliability Issues** and **Performance Degradation** compromising diagnostic accuracy, non-destructive material evaluation and treatment efficacy [8]-[9].

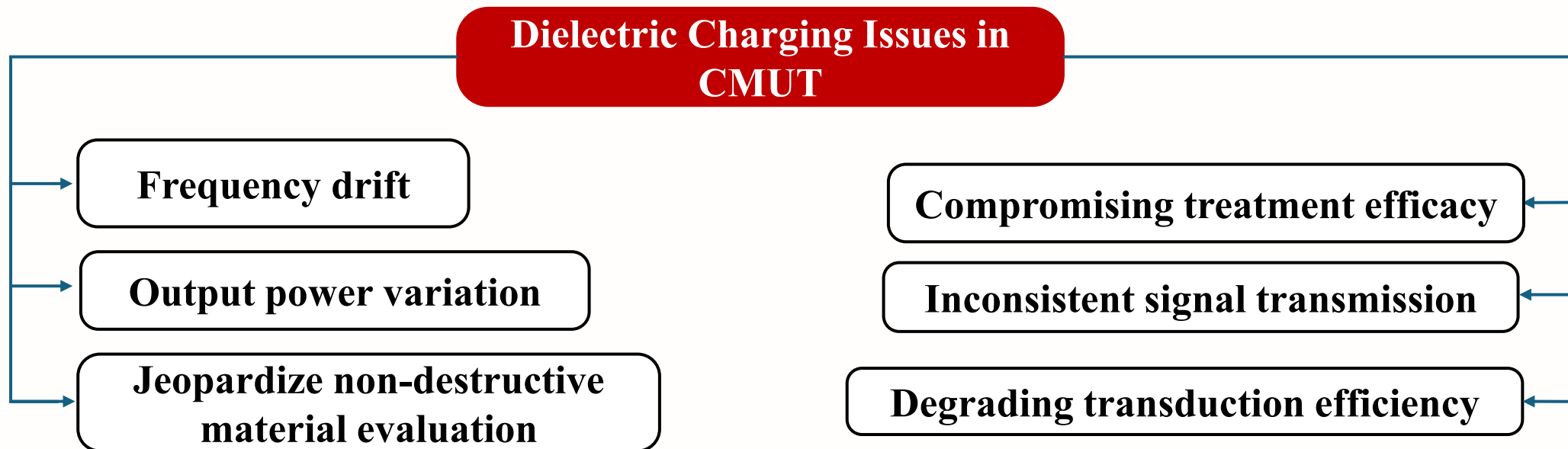


Figure 5: Challenges of a CMUT due to dielectric charging.

- Minimization of dielectric charging is crucial for enhancing CMUT efficiency and reliability.
- Current mitigation strategies for dielectric charging are insufficient.
- **It is necessary to investigate the fundamental causes of dielectric charging beyond the current state-of-the-art to develop methods to minimize the effects of dielectric charging to improve CMUT performance and reliability.**

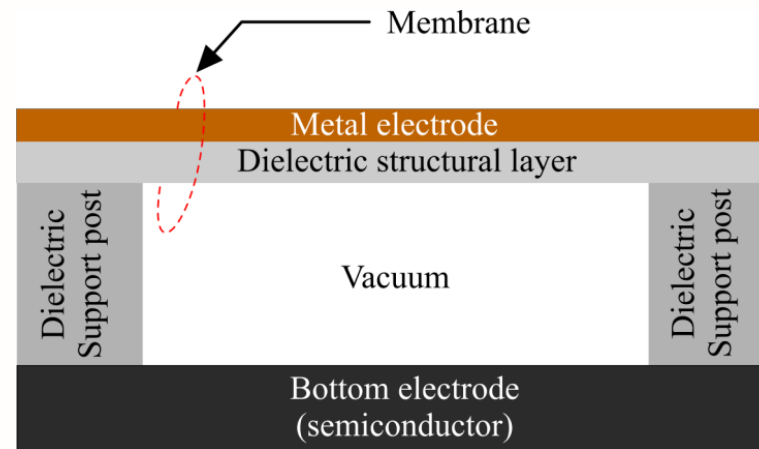


Figure 6: A typical CMUT Geometry

➤ The dielectric charging mechanisms in a CMUT include:

1. Quantum mechanical tunneling of electrons from the metal electrodes to the nitride membrane.
2. Internal Schottky effect due to the *K*-center defects (traps) in silicon nitride thinfilms that are used to realize the structural layers of the CMUT membranes

This research work investigates the dielectric charging in CMUT silicon nitride membranes due to the internal Schottky effect

Literature Survey

Representative Solution Approaches



Reference	Year	Scientific approach	Results
[10]	2005	Introduced isolation posts on the dielectric material instead of using the whole layer in order to reduce the surface area of the insulation layer.	The resulting CMUT geometry exhibited stable CV characteristics with reduced charging even at high voltage cycling.
[11]	2010	1D model of 2-layer dielectric CMUT geometry was presented. The model considered only the surface-level charge build up and disregarded any volumetric effects.	Minimizing the dielectric surface roughness significantly reduces surface charge accumulation.
[12]	2015	The CMUT is equipped with mechanical spacers below the vibrating membrane and partial openings on the electrode above the spacers to limit a direct contact surface area with the substrate.	The proposed structure reduced the receiving sensitivity fluctuation by 1dB after membrane vibration of 6×10^{11} cycles, which enabled a three times increase in transmitted acoustic pressure, indicating substantial performance gains.
[5]	2020	This model applied the electron transport models which are Poole-Frenkel and Fowler-Nordheim to calculate the current densities and support optimized designs.	Decreasing the membrane thickness, height of cavity, insulation layer, and temperature decreases output current density, thereby minimizing dielectric charging.

- Literature reviews on dielectric charging: Establish the state-of-the-art
- Investigation of CMUT membrane materials: Identify the most suitable option for membrane construction, ensuring improved mechanical and electrical performance.
- Mathematical modeling: Using theoretical models such as the **Poole-Frenkel** and **Hartke** models to investigate the charge trapping of electrons leading to dielectric charging of the CMUT.
- Conduct **MATLAB-based simulations** to better understand the dielectric charging effect.
- Result comparison
- Conduct a MATLAB-based simulation to investigate the effect of dielectric **material composition** on the resultant output current density leading to dielectric charging.

Material Exploration: Silicon Nitride Membrane



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- Microfabricated thin silicon nitride films functionalized with a thinfilm of gold, is a popular choice to fabricate CMUT membranes due to its high mechanical strength and low residual stress.
- Silicon nitride is a hard material from the family of ceramics consisting of silicon and nitrogen.
- Microfabricated silicon nitride thinfilms are typically deposited using two primary methods: Low-Pressure Chemical Vapor Deposition (LPCVD) and Plasma-Enhanced Chemical Vapor Deposition (PECVD).
- While both techniques are extensively utilized across various applications, they differ significantly in many aspects as listed in Table 2.

Table 2. Silicon Nitride Thinfilm Physical Properties for LPCVD and PECVD.

Property	LPCVD	PECVD	Unit
Deposition temperature	973 – 1073	473 – 673	K
Particles	Few	Many	
Step coverage	Conformable	Poor	
Dielectric constant	6 – 7	6 – 9	
Residual stress	1000T	-1100C – 500T	MPa
Young's modulus	270	300	GPa
Film quality	Excellent	Poor	
Dielectric strength	10	5	V/m
Resistivity	10^{14}	10 - 10^{13}	Ω -m

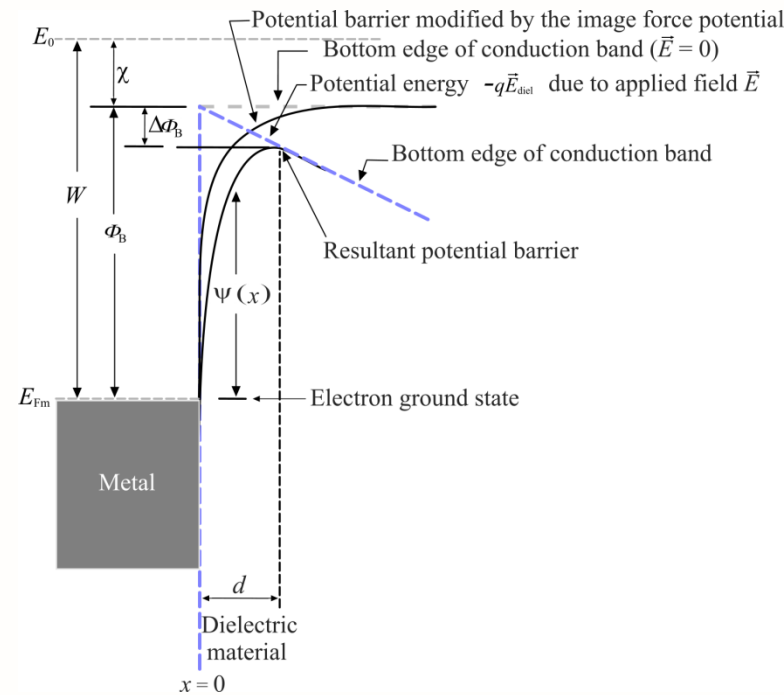
Note: C = compressive; T = tensile

Potential Energy Distribution in Silicon Nitride Trap Centers



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- The potential energy barrier lowering due to an applied electric field is known as the Schottky effect.
- In a dielectric material, such as silicon nitride with trap centers, an applied bias voltage-induced electric field also lowers the potential energy depth of the trap center in a similar fashion and is known as the internal Schottky effect [15].



E_{FM}	Metal Fermi level
W	Metal work function
χ	Insulator electron affinity
$\vec{E}$	Applied electric field
d	Dielectric thickness
ϕ_B	Potential barrier height
$\Delta\phi_B$	Decrease in potential barrier height
$\psi(x)$	Resultant potential barrier

Figure 7. Potential energy barrier lowering in a typical metal-dielectric emission system due to an applied electric field.

Potential Energy Distribution in a CMUT

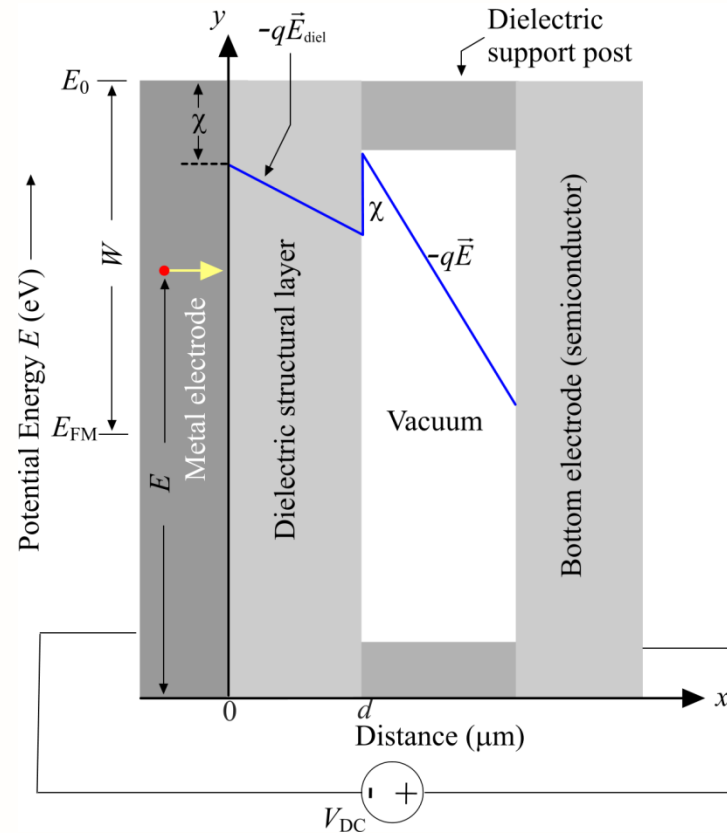


Figure 8. CMUT model showing the triangular barrier lowering due to an applied electric field.

K-Center Defects in Silicon Nitride Films



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- Dielectric charging in silicon nitride thinfilms arises mainly from silicon dangling bonds (*K*-centers or traps) that act as amphoteric traps, capturing both electrons and holes.
- These traps have energy states of 4.2eV for a silicon and -2eV for a nitrogen dangling bond, which suggests that nitrogen contributes minimally to charge trapping [16].
- This defect is diamagnetic when either positively charged k^+ (no spin) or negatively charged k^- (two spin) but paramagnetic when neutral (k^0).
- Thermally emitted trapped charges due to internal Schottky effect from *K*-centers contribute to current density, likewise tunneling current arising from charge injection between the metal electrode and silicon nitride.

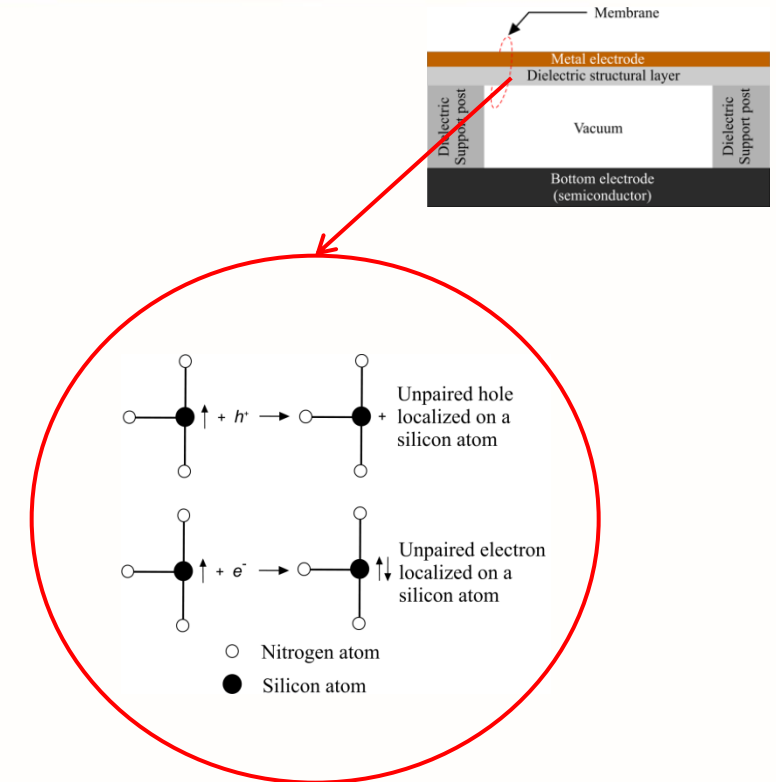


Figure 9. Schematic diagram of the *K*-centers showing an unpaired electron localized on a silicon atom and bonded to three Nitrogen.

Poole-Frenkel Model



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- If the potential barrier lowering due to the internal Schottky effect is sufficient, a trapped electron can overcome the potential barrier and be transported to the conduction band.
- As the trapped charges are transported to the conduction band, they contribute to dielectric charging and in turn, a leakage current.
- There exist two models to predict the current density due to the internal Schottky effect: 1. **The Poole-Frenkel (PF) emission model**, and 2. **The Hartke emission model**.
- The PF emission current density can be calculated from

$$J_{\text{PF}} = N\mu\vec{E} \exp\left[\frac{-q(\phi - \Delta\phi)}{k_{\text{B}}T}\right] \quad (7)$$

$$\Delta\phi = \left(\frac{q^3}{4\pi\epsilon_0\epsilon_r}\right)^{\frac{1}{2}} \vec{E}^{\frac{1}{2}} \quad (8)$$

N Trap density

μ Effective carrier mobility

$\vec{E}$ Electric field

$\Delta\phi$ Barrier lowering

ϵ_0 Permittivity of free-space

ϵ_r Relative permittivity of the material

k_{B} Boltzmann constant

ϕ Trap depth

3-D Hartke Model



- The Poole-Frenkel (PF) emission model is uni-directional (e.g., along the x -direction as in Figure 10).
- In reality, charge emissions from the trap centers due to the internal Schottky effect are not uni-directional but occur over a range of directions in a 3D space (Figure 10)

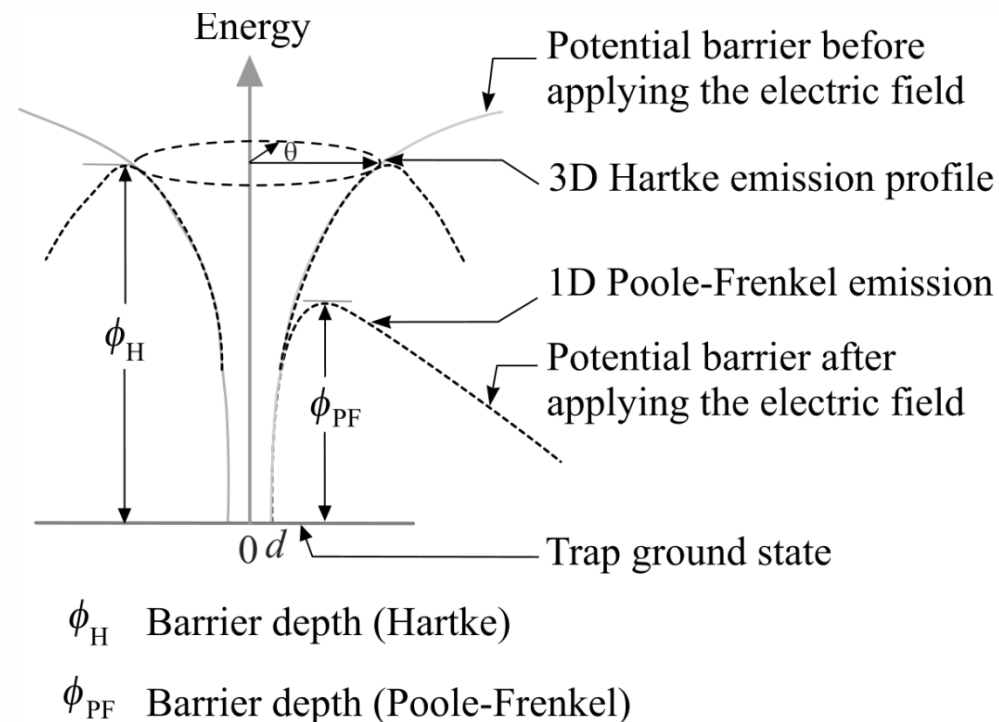


Figure 10. Schematic diagram of a 1D Poole-Frenkel and 3D Hatke models of electron emission showing an emitting electron from a conceptual trap depth due to potential barrier lowering.

3-D Hartke Model (cont.)



- The Hartke emission model accounts for this internal Schottky effect in a 3D space by introducing angular dependencies where the barrier lowering varies with the angle θ between the direction of the applied field and the emission path, described as $\Delta\phi_{PF}\cos\theta$ [17].
- When this relationship is integrated over all possible emission angles, the effective average barrier can be calculated with better accuracy.
- The emission current density according to the Hartke model, resulting from the electric field associated with the CMUT bias voltage, is expressed as

$$J_{3-D} = \exp\left(\frac{-\phi}{k_B T}\right) \left(\frac{k_B T}{\Delta\phi \sqrt{E}}\right)^2 \left(1 + \left(\left(\frac{\Delta\phi \sqrt{E}}{k_B T}\right) - 1\right) \exp\left(\frac{\Delta\phi \sqrt{E}}{k_B T}\right)\right) + \frac{1}{2} \quad (9)$$

where $\Delta\phi$ is the barrier-lowering coefficient, and other parameters remain the same as in (8)

$$\Delta\phi = \left(\frac{q^3}{\pi\epsilon_r\epsilon_0}\right)^{\frac{1}{2}} \quad (10)$$

Test CMUT Specifications

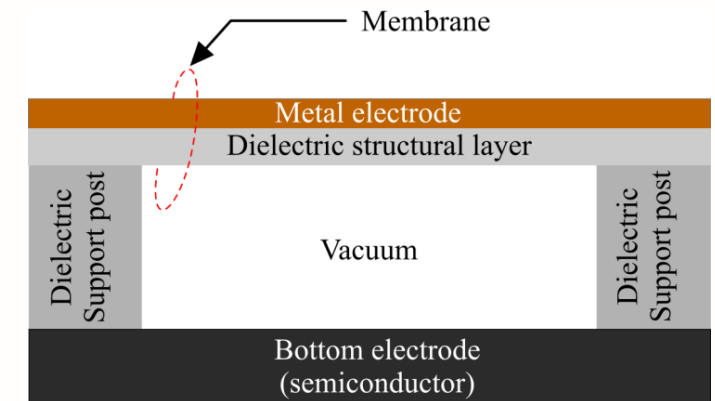


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- To compare the models, a CMUT with the specifications listed in table 3 was used

Table 3. CMUT Specifications [18, 19].

Parameters	Dimension	Unit
Gold electrode thickness	0.4	μm
Silicon nitride layer thickness	0.5	μm
Vacuum gap thickness	0.6	μm
Bottom electrode thickness (silicon)	500	μm



Emission Current Density



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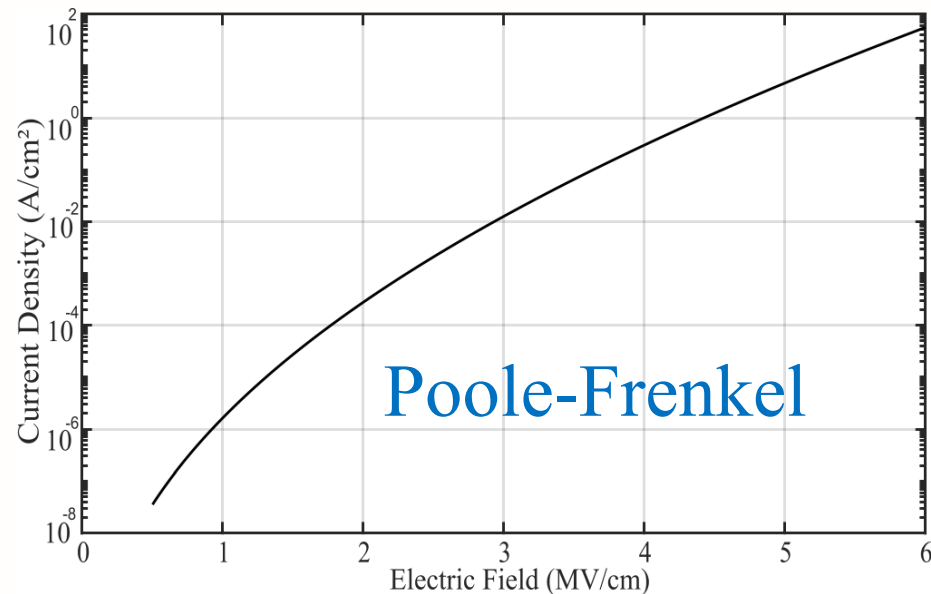


Figure 11. Poole-Frenkel model predicted current density due to the trap centers in the CMUT silicon nitride membrane as a function of the electric field associated with the CMUT bias voltage.

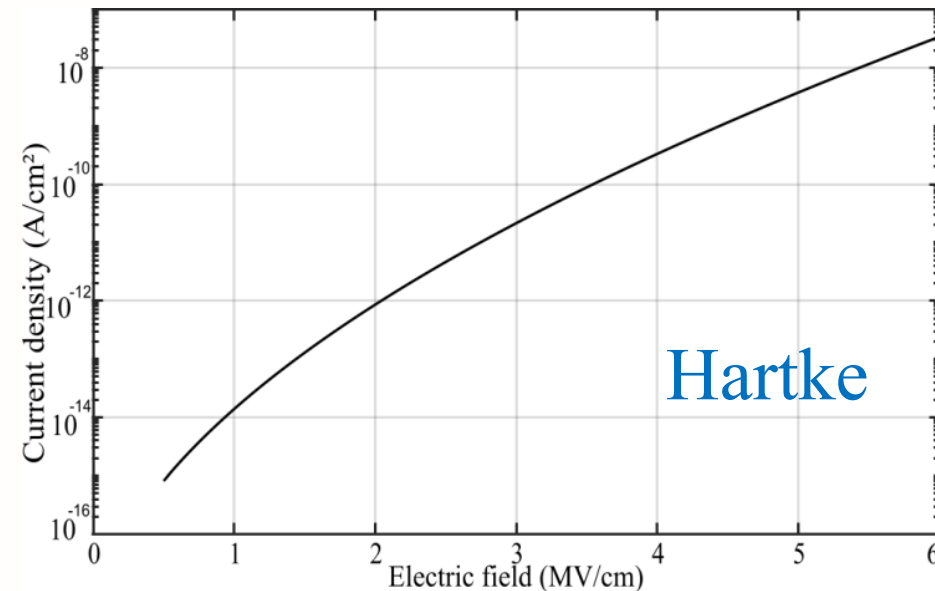


Figure 12. 3D Hartke model predicted current density due to the trap centers in the CMUT silicon nitride membrane as a function of the electric field associated with the CMUT bias voltage.

- Comparison of Hartke and Poole-Frenkel emission models predicted current densities

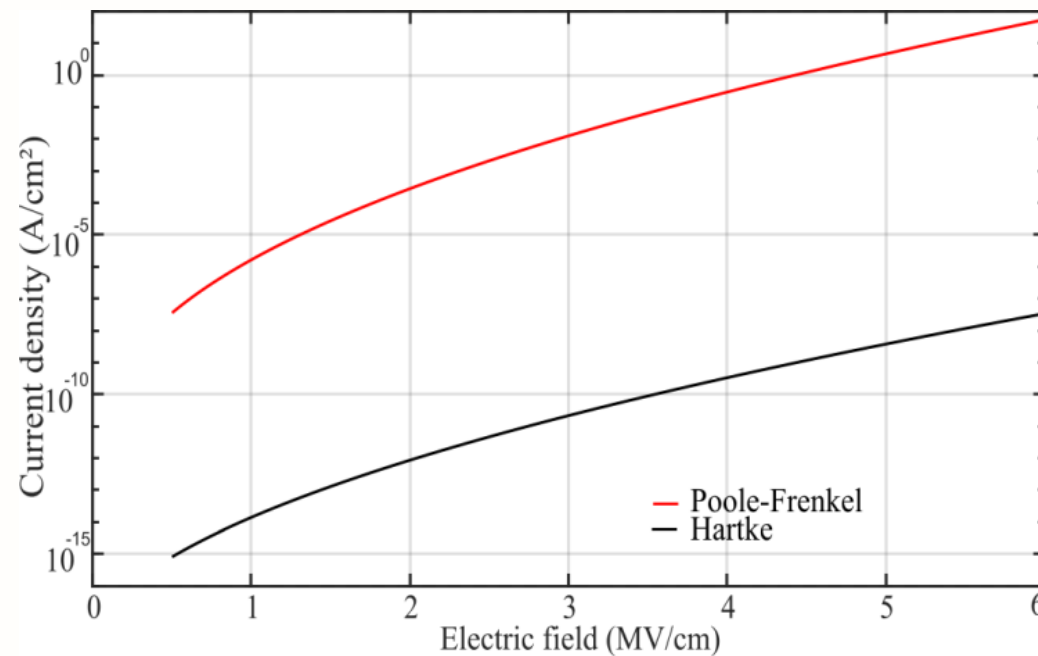


Figure 13. Comparison of Hartke and Poole-Frenkel emission models predicted current densities.

Results:

PF and Hartke Model Current Density Comparison



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Table 4. Current Density Comparison.

Bias Voltage (V)	Hartke model current density. A/cm ²	Poole-Frenkel model current density. A/cm ²	$\Delta\% = \frac{J_{PF} - J_H}{J_{PF}} \times 100$
11	2.689×10^{-12}	1.077×10^{-10}	97.5
22	8.154×10^{-12}	8.771×10^{-10}	99.0
33	2.016×10^{-11}	3.864×10^{-9}	99.47
44	4.425×10^{-11}	1.277×10^{-8}	99.65
55	8.950×10^{-11}	3.555×10^{-8}	99.83
66	1.704×10^{-10}	8.796×10^{-8}	99.80
77	3.099×10^{-10}	1.996×10^{-7}	99.84

Current Density Variation Based on Nitrogen Content in Silicon Nitride Membrane



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- The trap density in a silicon nitride layer depends on the actual composition of silicon and nitrogen in the nitride layer originating from the actual microfabrication process, such as PECVD or LPCVD, it is worth investigating the current densities as a function of the silicon and nitrogen content in the nitride layer.
- To conduct this investigation, three different silicon nitride layers with varying silicon and nitrogen compositions as listed in Table 5 were used [20]. Corresponding current densities as a function of bias voltage associated electric field are plotted.
- As it can be seen in Figure 14, the layer with the lowest nitrogen content has lower trap depth and, consequently, higher emission current density for the same applied electric field

Table 5. Different LPCVD Silicon Nitride Compositions with Corresponding Trap Depths.

Composition	Trap depth/ionization potential ϕ (eV)
$\text{SiN}_{0.75}$	0.56
$\text{SiN}_{1.17}$	0.92
$\text{SiN}_{1.22}$	1.13

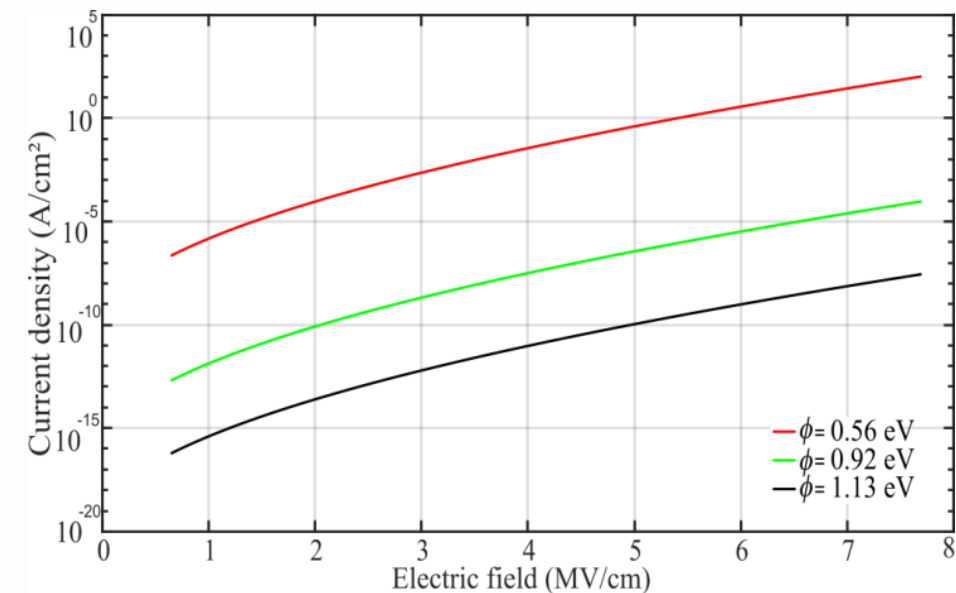


Figure 14. The Hartke model predicted current densities for three different silicon nitride layers with varying composition of silicon and nitrogen and trap depth energy levels.

Conclusions



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- This investigation revealed that the Poole-Frenkel effect (internal Schottky effect due to the K-center defects) contributes significantly higher, as high as 99%, towards the overall dielectric charging of silicon nitride membranes used in CMUTs.
- The study also revealed that the 3D Hartke model is more realistic and more accurate compared to the 1D Poole-Frenkel model to predict trap-assisted current density in silicon nitride membrane CMUTs
- It has also been observed that the higher the nitrogen content in a silicon nitride film, the lower is the trap-assisted current density, as predicted by the 3D Hartke model.
- The research results can be used to design higher reliability CMUTs

RESEARCH SPONSORS



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- Natural Sciences and Engineering Research Council of Canada (NSERC)
- IntelliSense Corp, 220 Broadway, Suite 102, Lynnfield, MA 01940, USA

REFERENCES



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- [1] M. Ieda, G. Sawa, and S. Kato, “A Consideration of Poole-Frenkel Effect on Electric Conduction in Insulators,” *Journal of Applied Physics*, vol. 42, no. 10, pp. 3737–3740, Sep. 1971, doi: 10.1063/1.1659678.
- [2] K. Brenner, A. Ergun, K. Firouzi, M. Rasmussen, Q. Stedman, and B. Khuri–Yakub, “Advances in Capacitive Micromachined Ultrasonic Transducers,” *Micromachines*, vol. 10, no. 2, p. 152, Feb. 2019, doi: 10.3390/mi10020152.
- [3] C. Herickhoff and R. Van Schaijk, “CMUT technology developments,” *Zeitschrift für Medizinische Physik*, vol. 33, no. 3, pp. 256–266, Aug. 2023, doi: 10.1016/j.zemedi.2023.04.010.
- [4] J. Li, Y. Li, and P. Zhang, “Modelling and Analysis of Dielectric Charge of CMUTs,” *IOP Conference Series: Material Science and Engineering*, vol. 768, no. 6, Mar. 2020, p. 062106, doi: 10.1088/1757-899X/768/6/062106.
- [5] M. Koutsourelis, D. Birbilitis, L. Michalas, and G. Papaioannou, “Dielectric charging in MEMS capacitive switches: a persisting reliability issue, available models and assessment methods,” in *Proc. 16th Mediterranean Microwave Symposium (MMS)*, Abu Dhabi, United Arab Emirates: IEEE, Nov. 2016, pp. 1–4. doi: 10.1109/MMS.2016.7803802.
- [6] J. Munir, Q. Ain, and H. Lee, “Reliability issue related to dielectric charging in capacitive micromachined ultrasonic transducers: A review,” *Microelectronics Reliability*, vol. 92, Jan. 2019, pp. 155–167, doi: 10.1016/j.microrel.2018.12.005.
- [7] M. Rayyan, K. Kratkiewicz, and K. Avanaki, ‘Overview of Ultrasound Detection Technologies for Photoacoustic Imaging’. *Micromachines*, Jul. 2020 11.7, p. 692. DOI: 10.3390/mi11070692
- [8] N. Tavassolian, “Dielectric charging in capacitive RF MEMS switches with silicon nitride and silicon dioxide,” PhD dissertation, Electrical and Computer Engineering, Georgia Institute of Technology, Georgia, USA. May 2011.
- [9] J. Munir, Q. Ain, and H. Lee, “Reliability issue related to dielectric charging in capacitive micromachined ultrasonic transducers: A review,” *Microelectronics Reliability*, vol. 92, pp. 155–167, Jan. 2019, doi: 10.1016/j.microrel.2018.12.005.
- [10] P. Zhang, G. Fitzpatrick, W. Moussa, and R. J. Zemp, “CMUTs with improved electrical safety & minimal dielectric surface charging,” in *Proc. IEEE International Ultrasonics Symposium*, San Diego, CA, USA: IEEE, Oct. 2010, pp. 1881–1885. doi: 10.1109/ULTSYM.2010.5935744.

REFERENCES



- [11] J. Hernandez, T. Zure, S. Chowdhury, Capacitance measurements of an SOI based CMUT”, in *Proc. IEEE 4th Latin American Symposium on Circuits and Systems (LASCAS)*, Cusco, Peru, 2013, pp. 1-4, doi: 10.1109/LASCAS.2013.6519037.
- [12] S. Machida, T. Takezaki, T. Kobayashi, H. Tanaka and T. Nagata, "Highly reliable CMUT cell structure with reduced dielectric charging effect," in *Proc. IEEE International Ultrasonics Symposium*, Taipei, Taiwan, 2015, pp. 1-4, doi: 10.1109/ULTSYM.2015.0061.
- [13] R. Pratap, A. Arunkumar, “Material selection for MEMS devices,”. *Indian Journal of Pure Applied Physics*, vol. 45, no.4, pp. 358–367, April 2007.
- [14] D. Choi, “Numerical Modelling of Space Charge Dynamics and Electrical Breakdown in Solid Dielectrics,” Ph.D. dissertation, Materials Science and Engineering, Pennsylvania State University, Pennsylvania USA. 2013.
- [15] U. Zaghloul *et al.*, “Nanoscale characterization of the dielectric charging phenomenon in PECVD silicon nitride Thinfilms with various interfacial structures based on Kelvin probe force microscopy,” *Nanotechnology*, vol. 22, no. 20, p. 205708, May 2011, doi: 10.1088/0957-4484/22/20/205708.
- [16] L. Warren, F. Rong, E. Poindexter, G. Gerardi, and J. Kanicki, “Structural identification of the silicon and nitrogen dangling-bond centers in amorphous silicon nitride,” *Journal of Applied Physics*, vol. 70, no. 1, pp. 346–354, Jul. 1991, doi: 10.1063/1.350280.
- [17] L. Hartke, “The Three-Dimensional Poole-Frenkel Effect,” *Journal of Applied Physics*, vol. 39, no. 10, pp. 4871–4873, Sep. 1968, doi: 10.1063/1.1655871.
- [18] T. Mohammed, R. Muscedere, and S. Chowdhury, “CMUT cavity pressure measurement using an atomic force microscope,” *Microsystem Technology*, vol. 30, no. 3, pp. 343–352, Mar. 2024, doi: [10.1007/s00542-024-05618-x](https://doi.org/10.1007/s00542-024-05618-x).
- [19] R. Manwar and S. Chowdhury, “Characterization of adhesive wafer bonded CMUTs realized from BCB based sealed cavity,” in *Proc. IEEE International Symposium on Circuits and Systems (ISCAS)*, Montréal, QC, Canada, May. 2016, pp. 2531–2534. doi: 10.1109/ISCAS.2016.7539108.
- [20] R. Apodaca, “Electrical Characterization of Silicon-Rich Nitride and Silicon Oxynitride Films Deposited by Low-Pressure Chemical Vapor Deposition,” M.S. thesis, Electrical Engineering, The University of New Mexico, Albuquerque, New Mexico. 2005.



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Thank You